FINAL REPORT

NASA GRANT : NAG-5-1498 (MIT OSP# 75226)

PROJECT : *Foreign Travel Grant for Science Collaborations Involving the ROSAT Observatory*

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DATE of REPORT December 23, 1994

GRANT PERIOD: April 1991 - April 1994

This NASA travel grant to M.I.T. facilitated travel for scientific collaborations with the group responsible for the ROSAT all-sky survey. The ROSAT Principal Investigators reside at the Max Planck Institute for Extraterrestrial Physics in Garching Germany; the travel grant was specifically intended to foster communication and the exchange of scientific information between M.I.T. and the ROSAT P.I. group. Below, we outline the travel activity associated with this grant and a summary of the goals and accomplishments derived from this research.

The M.I.T. research effort for ROSAT has become a multi-faceted program which is summarized below. In addition to the travel grant presently reported, additional funding was provided by a ROSAT science grant to Dr. Remillard (NAG 5-1784), which is still in progress. The ROSAT investigations are also supported, indirectly, with the use of facilities provided by the M.I.T. contract for the X-ray Timing Explorer (Prof. Bradt, P.I.).

Introduction

Between August 1990 and February 1991, the German X-ray Observatory, ROSAT, conducted a deep celestial survey at soft X-ray energies (0.1 to 2.4 keV). This historical effort yielded more than 70,000 X-ray sources with an imaging accuracy ~40". The large majority (85%) of these detections signified new objects that were unknown to astronomers. Furthermore, there is generally a lack of detailed knowledge for many of the "stars" in astronomical catalogs that *do* match the ROSAT positions. Thus, substantial optical spectroscopy is required for the identification of ROSAT X-ray sources and for the proper interpretations of the rich supply of timing and spectral information contained in the ROSAT Survey. M.I.T. researchers, Prof. Bradt and Dr. Remillard, were given this travel grant by NASA in order to join this effort. Data rights to the survey are entirely controlled by the ROSAT P.I. group at the Max Planck Institute (MPI) for Extraterrestrial Physics in Germany. The M.I.T. group brought significant expertise on the techniques of optical identifications of X-ray sources, and they also provided access to the optical telescopes at Michigan-Dartmouth-MIT Observatory at Kitt Peak, near Tucson Arizona. Some of the MIT investigations with ROSAT continue to be funded with a grant to Dr. Remillard under the NASA / Astrophysics / ROSAT program, and therefore some of the science programs described below are still "in progress", despite the completion of the travel grant for the development of these programs.

Table 1: Travel for Scientific Collaborations Involving the ROSAT Sky Survey

R. Remillard	Oct. 1991	First official meeting of the RGPS; attendance of 2nd Garching Workshop on CVs and LMXBs
H. Bradt	Aug. 1992	Negotiate use of ROSAT survey to confirm the identifications in the HEAO-1 flux-limited sample of hard X-ray sources; conduct pilot investigation for 22 HEAO-1 sources.
R. Remillard	Nov. 1992	attend scheduled RGPS meeting; organize the use of EXSAS programs to verify and derive improved X-ray flux meaasures for optically identified sources
R. Remillard	Oct. 1993	attend scheduled RGPS meeting; 10 days of programming and data analysis for ROSAT / HEAO-1 program

Summary of MIT Research Related to the ROSAT All-Sky Survey

(1) Identification of X-ray Sources in the ROSAT Galactic Plane Survey

Collaborators: Drs. Frank Haberl and Wolfgang Pietsch of MPE, and Dr. Christian Motch of the Univ. of Strassbourg

Just before the launch of ROSAT, the P.I. group formed a team of experienced collaborators to help identify optically the ~11,000 ROSAT sources that ROSAT would find within a $\pm 20^o$ strip centered on the galactic plane. The MIT group is a working member of this ROSAT Galactic Plane Survey (RGPS), which includes 9 research institutions, 2 of which are from the US. During the past 3 years, the MIT efforts yielded 342 optical identifications, the largest gain within the RGPS.

With regard to the identified X-ray sources, the first RGPS objectives are to produce a clear statement regarding the spectral class, a V magnitude, and remarks about noteworthy characteristics in either the optical or X-ray spectrum. ROSAT identification publications are proceed in two installments, based on area-selected ROSAT positions (i.e. including all of the X-ray sources in particular patches on the sky), and based on particular X-ray properties (e.g. sources that are bright, or those having spectra unusually 'hot' or 'cool' within the ROSAT bandwidth). Table 2 contains a summary of the 342 RGPS identifications gained thusfar. The identifications are concentrated in 8 spectral classes.

(2) ROSAT Confirmation of the Identifications for the Flux-Limited Sample of 332 Hard X-ray Sources from the HEAO-1 Survey

Collaborators: Prof. J. Trumper and Dr. W. Voges of MPE

The HEAO-1 Survey (1977–1979) remains the most complete celestial survey available in 'hard' X-rays. We have completed a long-term optical identification program for the 842 sources detected by the HEAO-1 Large Area Sky Survey (LASS; 2-20 keV; Wood et al. 1984, ApJS 56, 507), with the assistance of positions derived from the HEAO-1 Modulation Collimator (MC; 1–13 keV). The resulting MC–LASS Catalog of Identified X-ray Sources (Remilard et al. to be submitted to ApJS) contains ~700 objects concentrated in 8 spectral classes. We are particularly interested in the subset of the LASS catalog that constitutes a complete, flux-limited sample at high galactic latitude ($|b| > 20^o$, exluding the Magellanic Clouds). An examination of the statistical distribution of the LASS sources establishes a virtually complete sample of 332 sources with X-ray flux ≥ 0.0036 LASS cts c^{-2} s^{-1} (f_x > 0.9 μJy at 5 keV for a Crab–like spectrum). Optical identifications have been proposed for 86% of these sources, which are highly concentrated in 5 spectral classes. Our second collaboration with MPE uses the imaging ROSAT survey (particularly the D-band or 1.0–2.4 keV flux) to both confirm and complete the identifications for the HEAO-1 flux-limited sample. The ROSAT imaging survey provides far better positions that the rectangular HEAO-LASS error boxes, which are ~2.0 x 0.20 degrees near the threshold for the flux-limited sample. We have worked out a means of determining the confidence that a given HEAO-1 X-ray identification is correct, based on the flux and local dominance of that source in the ROSAT D-band, near the HEAO-LASS error box. The ROSAT / HEAO-1 comparison has generated the need to gain *optical* identifications for some high-latitude ROSAT sources, and the progress in securing such identifications is reported in Table 3.

Our investigation have gained important new X-ray identifications, and the overall effort is presently enabling a confident reassessment of statistical studies related to the HEAO-1 sample. Hard X-ray selection emphasizes a distinct set of X-ray classes, and the flux measurements are relatively free from the effects of absorption due to interstellar column densities that are typical at high galactic latitudes. Some of the specific class studies we have been engaged in are listed below (Andrew Silber, Ph D. thesis 1992; Bruce Grossan, Ph D. thesis 1992; Erling Ho, senior thesis 1992; Lerothodi Leeuw, senior thesis 1992). Many of these topics are highly complementary to the class studies that will be based on samples and flux measurements derived from the ROSAT survey.

- Hard X–ray Luminosity Function of Active Galactic Nuclei (AGN Types 1 and 2)
- Hard X–ray Luminosity Function of Clusters of Galaxies
- Hard X–ray Luminosity Function of BL Lac Objects
- Multifrequency Correlation Studies of AGN Continua
- Correlation Studies of AGN X-ray Flux and Emission Lines
- Number Densities of X-ray Selected Cataclysmic Variables (CV)
- Frequency of Magnetic Subclasses in a Hard X-ray Sample of CVs
- Hard X-ray Luminosity Distributions of Stellar Subclasses with Active Coronae
- Hard vs. Soft X-ray Flux for Sources in the HEAO-1 Sample

(3) Optical Identification and Study of ROSAT "Supersoft" X-ray Sources

Consultations with: Dr. J. Greiner of MPE;
data obtained from the public database for ROSAT pointed observations.

Supersoft X-ray sources exhibit an extreme type of celestial X-ray spectrum that is remarkably steep, in the sense of an abundance of low-energy X-rays, compared to the previously known classes of X-ray sources. The first supersoft sources were discovered during a survey of the LMC with the *Einstein* satellite. The all-sky X-ray survey that was recently carried out with *ROSAT* has now established that a group of luminous supersoft X-ray sources constitute a distinct astronomical class (Hasinger 1994; Greiner, Hasinger, & Kahabka 1991; Schaeidt, Hasinger, & Truemper 1993; Orio & Ogelman 1993; Hertz, Grindlay, & Bailyn 1993; Greiner, Hasinger, & Thomas 1994). Most of the identified optical counterparts exhibit blue continua with emission lines of H and He II. The known or suspected luminous supersoft sources include 6 in the LMC, 4 in the SMC, 2 in our Galaxy, and at least 15 in M31 (Hasinger 1994). Two of these are well established binaries in the LMC, including CAL 83 with V ~ 17 and an orbital period of 1.04 days (Smale et al. 1988; Pakull et al. 1988; Cowley et al. 1990).

A particular model for at least a large subset of these systems invokes steady nuclear burning of accreted matter on the surface of a ~ 1 $M_\odot$ white dwarf. The companion star is expected to be a main-sequence or subgiant star of ~1.3 – 2.7 $M_\odot$, and mass transfer rates of between 1 and 4 × 10^{-7} $M_\odot$ yr^{-1} are required to sustain the luminosity (van del Heuvel et al. 1992; Rappaport, DiStefano, & Smith 1994). Such high transfer rates are a natural consequence of unstable mass transfer via Roche lobe overflow from a more massive donor star to the less massive accreting white dwarf. Models for the evolution of these systems (Rappaport, DiStefano, & Smith 1994) predict that the orbital periods should lie in the range of 8 hr to ~1.5 days, and that there should be some 10^3 such systems in the Galaxy and in M31. In spite of the greater distance, it is apparently easier to detect luminous supersoft sources (at least in the soft X-ray band) in nearby external galaxies viewed at relatively high galactic latitude, such as the LMC (–33°) and M31 (–21°), than it is in the plane of our own Galaxy because a hydrogen column density of only a few times 10^{21} cm^{-2} will absorb most of the very soft X-radiation (DiStefano & Rappaport 1994).

Regardless of the physical model for the luminous supersoft X-ray sources, it is clear that they emit copious quantities of highly ionizing photons in the range 20 – 200 eV. Thus, we expect that there will be an ionization nebula surrounding these sources (Rappaport et al. 1994). The detection of an ionization nebula around a supersoft X-ray source should lead to a better understanding of both the source luminosity and the properties of the surrounding interstellar medium (ISM). The strength of the ionization nebula will depend on how much soft X–radiation is able to escape, in all directions, from the immediate environment of the binary system. This could provide a more accurate measure of the X-ray luminosity than can be made by direct X-ray observations since, in a sense, the ISM acts as a giant bolometer. By contrast, only the high-energy 'tail' of the supersoft X-ray source spectrum can be directly observed since the bulk of the emission in the extreme UV is absorbed by the ISM. Studies of the ionization nebulae surrounding supersoft X-ray sources could also shed some light on the evolutionary past of these binary systems. In particular, such investigations may reveal evidence for possible matter ejected in the form of a stellar wind from the massive star that was the progenitor of the white dwarf and/or matter ejected during a common envelope phase in which the envelope of the progenitor was stripped off.

Efforts for investigations of ROSAT supersoft X-ray sources are twofold. First, we are attempting to identify all of ROSAT's very soft X-ray sources in order to locate new cases of the particular class that may be related to the luminous binaries in which there may be steady nuclear burning on the surface of a whgite dwarf. Secondly, we wish to study the images of the latter category in order to detect and study the ionization state of the local interstellar medium. Progress in this project is also reported in the second column of Table 3.

Publications and Papers in Preparation

"A ROSAT Glance at the Galactic Plane", C. Motch, T. Belloni, D. Buckley, M. Gottwald, G. Hasinger, S. A. Ilovaisky, M. W. Pakull, W. Pietsch, K. Reinsch, R. A. Remillard, J.H.M.M. Schmitt, and J. Trumper, *Astron. & Astrophys.*, 246, L24 (1991).

"A New X-ray Eclipsing AM Her Type Variable, RX J1802.1+1804", J. Greiner, R. Remillard, & C. Motch, 1994, Procs., Padua Conference on Cataclysmic Variables, in press.

"Ionization Nebulae Surrounding CAL 83 and Other Supersoft X-Ray Sources", R. A. Remillard, S. Rappaport, & L. M. Macri, *Astrophysicsl Journal*, 1995 February 1, in press.

"180 Identifications of Area-Selected X-ray Sources from the ROSAT All-Sky Survey", R. A. Remillard, F. Haberl, W. Pietsch, C. Motch, & H. V. Bradt, in preparation.

"162 Optical Identifications of X-ray Seleted Sources from the ROSAT All-Sky Survey", R. A. Remillard, F. Haberl, W. Pietsch, C. Motch, & H. V. Bradt, in preparation.

Table 2: 342 RGPS IDs from MIT

X-ray Positions (795)

	Area Selected	X-ray Selected	Total
# from ROSAT RGPS	550	245	**795**
# with Optical Work	405	191	**596**

Galactic Identifications (297)

Active Corona	103	105	**208**
'Normal' corona	39	20	**59**
Early Type Stars (Stellar Winds)	9	2	**11**
CVs	2	3	**5**
Hot Stars	2	2	**4**
SNR / knots	4	6	**10**

Extragalactic Identifications (45)

AGN	14	12	**26**
Clusters of Gal.	5	9	**14**
BL Lac Objects	2	3	**5**
TOTAL IDs	180	162	342

Table 3: 79 MIT IDs from other ROSAT Databases

	All-Sky Survey High Latitude HEAO-1	PSPC Pointings Selected Supersoft	Total
# X-ray Positions	100	212	**312**
# with Optical Work	65	79	**144**
Galactic Identifications (58)			
Active Corona	24	9	**33**
'Normal' corona	8	4	**12**
CVs	1	0	**1**
Hot Stars	1	11	**12**
Extragalactic Identifications (21)			
AGN	7	3	**10**
Clusters of Gal.	3	0	**3**
BL Lac Candidates	5	3	**8**
TOTAL IDs	49	30	79